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Ion Heating in a Supersonic Plasma Flow for an Advanced Plasma Thruster

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Ion heating experiments are performed in a fast flowing plasma with an ion Mach number of nearly unity. RF waves with an ion cyclotron range of frequency is excited by a pair of loop antennas located at a divergent magnetic nozzle. Increase of plasma thermal energy $W_\perp$ measured by a diamagnetic coil is observed when the waves are excited with various azimuthal mode numbers in several magnetic nozzle configurations. It is most effective to heat ions of plasma flow to excite the waves with an azimuthal mode number of m= • 1. The heating efficiency is larger in the magnetic beach configuration than that in the uniform one.

1. Introduction

Recently a plasma flow is found to play an important role in space and fusion plasmas. Intensive researches to develop a fast flowing plasma with high particle and heat fluxes are required in basic plasma-physics as well as various industrial and space applications.

A magnetic-nozzle acceleration and ion heating in a fast flowing plasma attracts much attention in the advanced electric propulsion system. In the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project, the combined system of the ion cyclotron heating and the magnetic nozzle is proposed to control a ratio of specific impulse to thrust at constant power [1].

Plasma acceleration in a divergent magnetic nozzle has been successfully demonstrated in the HITOP device, where a transonic plasma flow (M_i is nearly unity) is converted into a supersonic one (M_i increases up to 3) through a divergent magnetic nozzle where no j • B acceleration is exerted [2-4].

Though an ion heating in a magnetically-confined plasma has been precisely investigated both theoretically and experimentally in many researches, few attempt of a direct ion heating for fast flowing plasmas by radio-frequency waves has been done. The condition of ion cyclotron resonance is expected to change drastically by the effect of a Doppler shift in a fast flowing plasma.

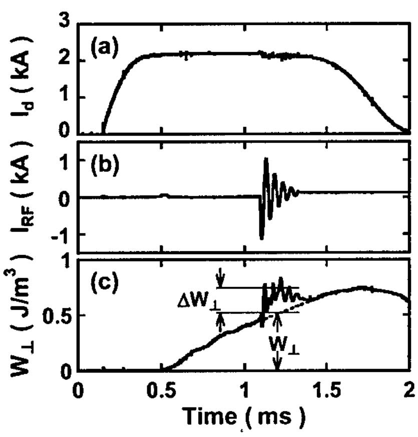

Fig.1 Temporal evolutions of (a) discharge current, (b) antenna current, (c) diamagnetic signal. The m= • 1 mode waves are excited in the magnetic-beach configuration.

In this experiment we have performed an ion heating experiment in a supersonic plasma flow produced in the HITOP device. Either axisymmetric (m=0) or non-axisymmetric (m= • 1 and • 2) mode waves near the ion cyclotron frequency is launched by a pair of loop-type antennas set in a diverging magnetic field. It is found that the plasma thermal energy measured by a diamagnetic loop coil increases when the waves are launched as a beach-heating configuration. The heating effects are compared in various wave excitation mode numbers and in several magnetic nozzle configurations.

2. Experimental Setup

Experiments are carried out in the HITOP device. It consists of a large cylindrical vacuum chamber (diameter D = 0.8m, length L = 3.3m) with eleven main and six auxiliary magnetic coils, which generate a uniform magnetic field up to 0.1T. Various types of magnetic field configurations can be formed by adjusting the external coil current.

A magneto-plasma-dynamic arcjet (MPDA) is installed at one end-port of the HITOP. It has been developed as a representative device for a space thruster [5] and is also utilized as a supersonic plasma flow source [3]. The MPDA has a coaxial structure and the plasma is accelerated axially by a self-induced electro-magnetic force, $F_z=J_r$ • B_θ where J_r is a radial discharge current and B_θ is self-induced azimuthal magnetic field.

Discharge current I_d up to 10kA is supplied by a pulse-forming network (PFN) system with the quasi-steady duration of 1ms. A high density (more than 10^{20}m^{-3}) and high Mach number (M_i up to 3) plasma flow can be generated.

Plasma flow characteristics are measured by several diagnostics installed on the HITOP device. Profiles of ion Mach number and plasma density along and across the field lines are measured by a movable Mach probe and an array of 13-channel Mach probes set at 1.7m downstream of the MPDA outlet in the HITOP [6].

3. Experimental Results

A pair of loop antennas with 60mm in diameter is used for the wave excitation [7]. Employing a Faraday shield reduces electrostatic coupling between the antenna and the plasma. The antennas are set at Z=1.0m downstream of the MPDA. The antenna current is supplied by a pulsed oscillation power-supply, which consists of a condenser and a gap-switch. The azimuthal mode number m of the exciting wave can be changed by adjusting the combination of the antenna-current direction.

In the present experiments, an argon gas is used due to a relatively low excitation frequency of about 20kHz. Figure 1 shows typical waveforms of the discharge current I_d, the antenna current I_{RF} and an observed diamagnetic signal $W_\perp$ under the condition of m= • 1 for the wave excitation mode. The plasma thermal energy $W_\perp$ is measured by a diamagnetic loop coil located at Z=2.2m. Though the antenna current damps rapidly due to the lack of power supply capability, the diamagnetic coil signal increases during the excitation.

The electron and ion temperature are almost equal at about 2eV and the density is 2 • 10^{19}m^{-3}. Plasma flow velocity can be estimated to be about 6km/sec by Mach probe measurements and a time delay of ion saturation current signals. It takes about 0.2ms for the Ar plasma to flow from the antenna position to the diamagnetic coil position. The $W_\perp$ signal, however, increases without such a delay time as shown in Fig. 1(c), which indicates that the waves propagate and absorbed in the downstream region. The wave phase velocity is about 10^5 m/s, which is measured by a phase shift of two magnetic probe signals located at axially-different positions.

We varied an azimuthal mode number of the excited waves by changing the coil arrangement. Figure 2 shows time evolutions of the diamagnetic signals with

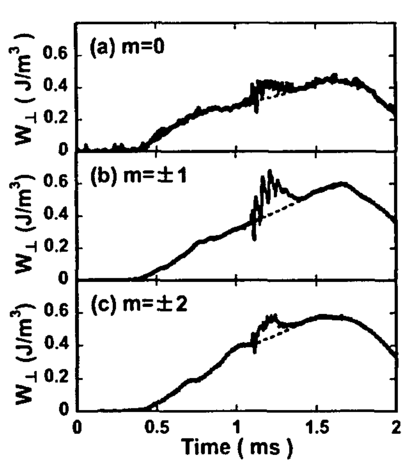

Fig.2 Temporal evolutions of diamagnetic signals in the three types of azimuthal mode number, (a) m=0, (b)m= • 1, (c)m= • 2.

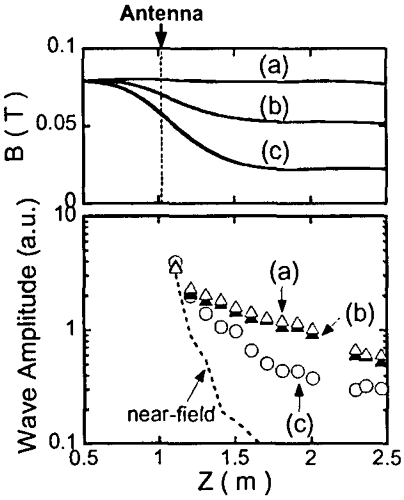

Fig.3 Three types of magnetic configurations. The wave is excited in ω/ω$_{ci}$<1 region and propagates downward approaching to the region of (a) ω/ω$_{ci}$<1 ,(b) ω/ω$_{ci}$=1, (c) ω/ω$_{ci}$>1. The wave amplitudes are measured in these configurations. The doted line corresponds to the case without plasma

three types of the azimuthal mode number, m=0, • 1, • 2. The increment ratio of the thermal energy ratio $\Delta W_\perp/W_\perp$ is the largest in the case of m= • 1.

Wave amplitude and phase shift are measured by magnetic probes at several axial positions in a uniform magnetic field. The obtained dispersion relation agrees well with that of shear Alfven waves. Damping of the excited wave amplitudes are measured and shown in Fig.3. The wave damping and the increment of $W_\perp$ are larger in the diverging magnetic configuration (type c) in these three types of magnetic configurations. The dependence on the magnetic strength does not show clear indication of the cyclotron resonance region. It should be caused by the Doppler effect of fast flowing ions.

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